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**ANALYSIS OF FOIL BEARINGS FOR  
HIGH SPEED OPERATION  
IN CRYOGENIC APPLICATIONS**



# ANALYSIS OF FOIL BEARINGS FOR HIGH SPEED OPERATION IN CRYOGENIC APPLICATIONS

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## I. Research Objective and Potential Impact on Propulsion

The general objective of this project is to develop analysis tools which are required for the design of foil bearings to be used in cryogenic applications. During the second year of this project, a general analysis approach and code for journal bearings operating under steady state conditions will be completed. This will be followed by the initiation of an investigation into transient behavior of foil bearings to determine their performance in rotor systems.

Foil bearings have been proposed as an alternative to rolling element bearings for use in cryogenic turbo-pumps in liquid propellant rocket engines. This type of bearing offers several advantages over rolling element bearings since they would use the cryogenic pump fluid for a lubricant and have structural flexibility. These bearings have the potential of high reliability and long life.

The bearing surface is constructed of a "foil" which resists deflection by a combination of bending, membrane, and elastic foundation effects(see figs. 1 and 2).

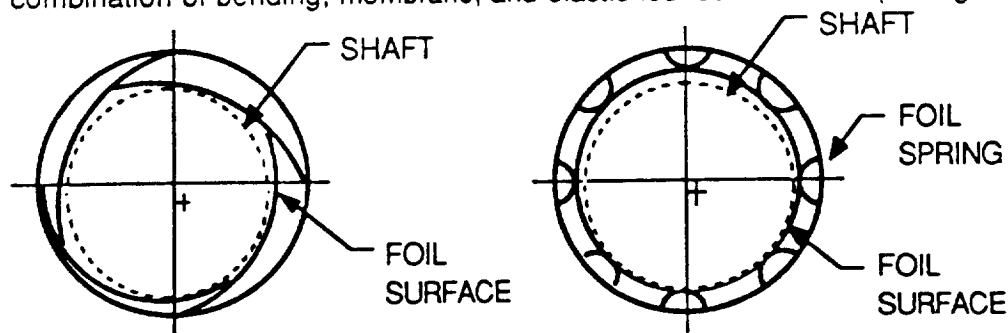


FIGURE 1 - LEAF TYPE BEARING

FIGURE 2 - HYDRESIL TYPE  
BEARING

The relative motion between the rotating shaft and the foil causes pressure in the fluid film to develop. This pressure deflects the foil surface away from the shaft. Once a full fluid film is established between the foil and the rotor shaft, contact no longer takes place and there is no subsequent wear of the surfaces. The flexible foil structure of the bearing allows it to compensate for minor tolerance and manufacturing defects. This same flexibility also has a significant effect on the dynamic performance of the rotor-bearing system.

## II. Current Status and Results

The initial efforts in this project have focussed on the development of a single unified approach which will address the broad range of possible configurations and operating conditions. A key part of the objective is to develop an analysis and code which is as modular as possible. The analysis process has been divided into two separate parts: determination of the nominal foil geometry for the bearing, and solution of the coupled foil deflection/fluid flow problem. After a discussion of this approach, results from a simple test configuration used to test the performance of solution approaches will be presented.

### 1. Calculation of Nominal Geometry

In a given design, the unconstrained foils can have arbitrary shapes and curvatures. A general nonlinear large displacement finite element formulation has been developed to calculate the nominal operating geometry of the foil. The formulation is used to calculate the nominal shape of the foil, the internal stresses in the foil, and the forces acting on the foil after the foil is assembled into the complete bearing. This information is then used to describe the foil in the coupled solution. The same deflection model, or a linearized version of it, can be used in the coupled solution.

### 2. Coupled Solution

The solution of the coupled problem requires the simultaneous calculation of the foil deflection, fluid flow, and the thermal transport. Within this project, a modified direct forward iteration approach has been developed for the solution of the coupled foil deflection/fluid flow problem. Direct forward iteration schemes normally utilize standard solution methods to iteratively calculate the displacement and the pressure. After each iteration, the deflection is updated and used to calculate a new pressure for the next iteration. The process is continued until the solution converges.

The iterative approach is modular and offers maximum flexibility in the development of alternate deflection and fluid models. The approach has been modified to incorporate the effects of the fluid flow, beyond the standard pressure coupling, into the finite element deflection calculation. This modification entails the addition of a stiffness matrix and loading vector based on the Reynolds equation to the deflection model. The Reynolds equation is still used to calculate the pressure in the fluid film from the clearance.

### 3. Results

The problem of an infinitely wide single foil bearing(see figure 3) has been used to test the modified direct forward iteration solution method. The foil is simply supported at the leading and trailing edges. A concentrated force is applied at the center of the foil. The slider, which is comparable in function to the shaft, is flat. This configuration is very similar to one of the foils which would be used in a multi-foil journal bearing configuration(see figure 4). In this case, the foil resists deflection by bending only.

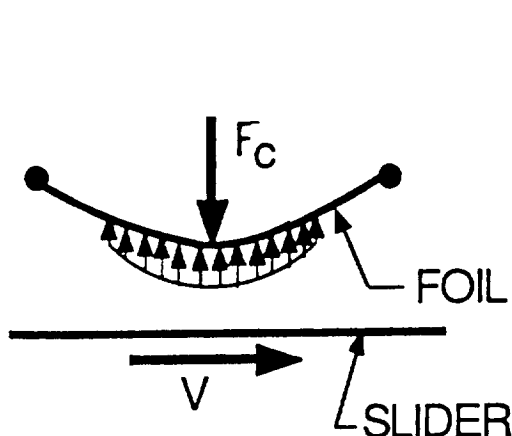


Figure 3 - Test configuration

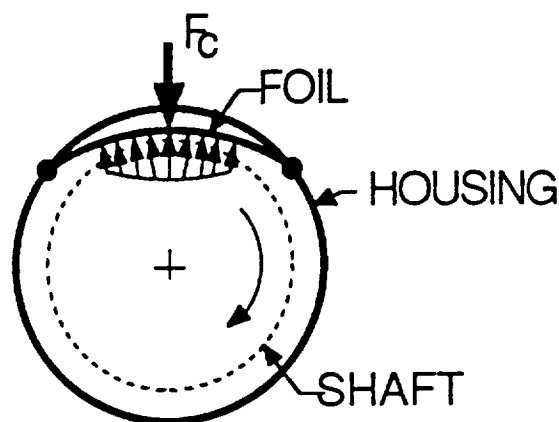


Figure 4 - Journal configuration

The significance of this new modified iterative approach is that it has significantly improved convergence characteristics compared to the standard direct iteration methods. This is of particular importance in heavily loaded bearings where the nominal deflection of the foil is large compared to the thickness of the fluid film. In heavily loaded cases, it is necessary to severely under-relax the displacement solution with very small relaxation factors to get converged solutions by standard direct iteration. The standard direct iteration solutions then require a large number of iterations, and convergence must be tested very carefully. The effectiveness of the modified iterative method is shown in figure 5, where the modified iterative approach converged significantly faster than the standard approach.

The clearance and pressure results of the modified iterative method for this same case are shown in figure 6. These results demonstrate the large change in clearance which is possible with this method. The method is very effective in preventing the clearance from becoming negative during the iteration process.

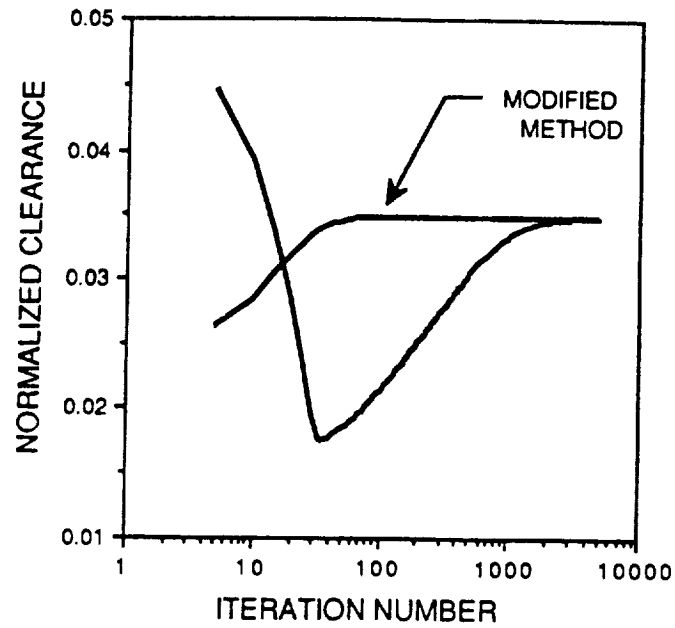


Figure 5 - Convergence of modified and standard iterative methods

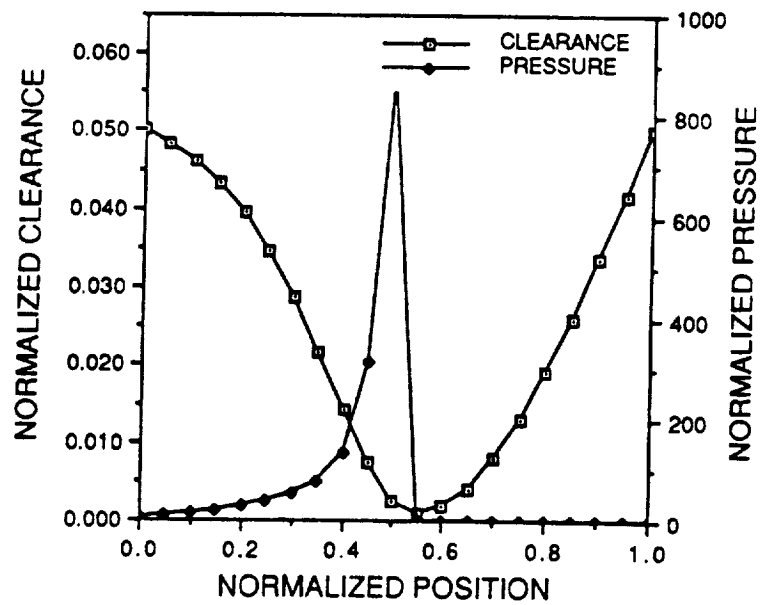


Figure 6 - Typical clearance and pressure distributions for heavily loaded bearing

### III. Proposed Work for Coming Year

The efforts in the next year will be split between: the completion of the analysis and code for the steady state performance of foil journal bearings, and the start of an investigation into the dynamic behavior of rotor systems utilizing foil bearings.

Many of the critical issues in the steady state analysis have been addressed and resolved. The following tasks in the steady state analysis will be completed:

1. Complete the development of a second finite element code specifically for the solution of coupled problems. This code will use output from the nonlinear large displacement calculation to define the nominal foil geometry. It will utilize the same basic finite element formulation to solve the coupled problem by iteratively operating on different data sets for the deflection and fluid flow in the bearing. This will be a two dimensional code.
2. Implement the general analysis for a finite width, multiple foil configuration. Several element types and subroutines will be installed in the code described in the previous task. Simple configurations will be implemented first to allow checking of more complicated cases.
3. Investigate the significance of thermal effects. The behavior of the fluid cannot be investigated until a basic working model has been developed. Results of these calculations may lead to modifications of the element types.

The initial stage of the investigation of the transient behavior of these bearings will focus on the development of a suitable model which can predict bearing stiffnesses and damping for use in rotor dynamic calculations. The following issues will have to be resolved:

1. The significance of foil to foil contact and rubbing in determining the stiffness and damping of bearings. The interfaces between foils are not frictionless and may significantly impact the transient bearing performance by modifying the stiffness and providing frictional losses.
2. The relative contributions of the fluid film and foil rubbing to the stiffness and damping. Although the stiffness of the system may be controlled by deflection of the foils, changes in foil shape will affect the fluid film.
3. The interfaces between the foils most probably behave as coulomb friction contacts. An equivalent viscous model will have to be developed to approximate the performance in standard rotor dynamics models.

These investigations form the basis of an approach to the development of a transient model for the bearings to be used in rotor dynamics applications.

